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Operationally merged satellite visible/IR and passive microwave sea ice information for improved sea ice forecasts and ship routing

W. Meier
NASA Goddard Space Flight Center, Cryospheric Sciences Laboratory, Greenbelt, MD 20771
Phone: 301-614-6572; email: walt.meier@nasa.gov

P. Posey
Naval Research Laboratory, Code 7322, Stennis Space Center, MS 39529
Phone: 228-688-5596; email: pamela.posey@nrlssc.navy.mil

L. Li
Naval Research Laboratory, Code 7223, Washington, DC
Phone: 202-767-0849; email: li.li@nrl.navy.mil

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BACKGROUND

The Arctic climate system is experiencing dramatic changes. One dramatic and very public change is the reduction in the summertime sea ice cover. The Intergovernmental Panel on Climate Change (IPCC) models predict a further decrease in sea ice cover with a potentially summertime ice-free Arctic before 2100. However, the projections vary widely, with some models predicting a summertime ice-free Arctic as early as 2040. Given the observed and forecast reduction in sea ice cover, Arctic shipping is expected to increase in the future. Additionally, the U.S. Navy and local fishermen need to adapt to the fast changing Arctic; it is vital for them to have access to accurate and timely information about the sea ice conditions at relatively small scales. This demands higher accuracy in sea ice forecasts.

Currently, the U.S. Navy uses the operational Arctic Cap Nowcast/Forecast System (ACNFS) for Arctic sea ice and ocean forecasting. ACNFS has been developed and validated using an Arctic grid resolution of approximately 3.5 km. From September 2013 – January 2015, the ice concentration fields from ACNFS have been updated with satellite-derived ice concentrations from DMSP Special Sensor Microwave Imager and Sounder (SSMIS) at a resolution of approximately 25 km. In February 2015, ACNFS was updated to assimilate both SSMIS and the 10 km resolution Advanced Microwave Scanning Radiometer 2 (AMSR2) satellite-derived ice concentration data. Higher resolution sea ice information from satellites is critically needed to augment these model resolution improvements.

LONG-TERM GOALS

The need for accurate ice forecasts is extremely important for U.S. Navy operations, shipping, and other activities. The goal of this project is to produce a merged visible/NIR/IR – passive microwave

high-resolution satellite derived sea ice concentration product and assimilate it into the Navy's ACNFS forecast system in order to improve the Navy's operational sea ice forecasts, especially in the Marginal Ice Zone (MIZ).

OBJECTIVES

The objective of this project is to develop an operational merged visible/NIR/IR – passive microwave sea ice concentration product for improved Navy sea ice forecasts. Specific tasks are:

1) Develop an improved sea ice concentration dataset that combines data from various satellites where the user automatically receives the best and most consistent sea ice concentration at the highest resolution available,
2) Implement an operational processing and data flow stream of newly merged high resolution data sources,
3) Ingest/assimilate this new dataset into the operational ACNFS sea ice forecast system.

APPROACH

AMSR2 (and its predecessor AMSR-E) passive microwave imagery provides complete daily fields of sea ice concentration in all sky conditions. Sea ice concentration is derived from the satellite obtained brightness temperature data using empirically derived algorithms. A main limitation of the currently available passive microwave imagery is low spatial resolution. The current SSMIS sea ice concentration product is available at 25 km resolution, while AMSR-E provided standard products on a 12.5 km grid and AMSR2 yields a 10 km grid. This is a considerable improvement over the long-term passive microwave from SSMIS that had been used by ACNFS; the SSMIS gridded products are at 25 km resolution, but some input channels have sensor footprints on the order of 70 km, resulting in a lower effective resolution. Since February 2015, along with the SSMIS ice concentration product, ACNFS has also ingested the AMSR2 ice concentration product, which recently became available in near real time (NRT).

In contrast to the low resolution available by passive microwave sensors, visible and infrared (IR) imagery provide sea ice information at higher spatial resolution, between 0.25 and 1.0 km for the Moderate Resolution Imaging Spectroradiometer (MODIS). The main limitation of visible/IR sensors is that, unlike passive microwave sensors, visible/IR sensors cannot retrieve data under all sky conditions, since they do not "see" through clouds. It is not unusual for clouds to prevent visible/IR satellite observations for more than 50% of the visible domain. The MODIS IR data may be used to derive sea ice concentration, as IR does not depend on daylight and can thus be used during polar darkness (c.f. visible and near IR data that can only be used in daylight). However, during the summer months the sea ice/snow surface may be at its melting temperature and thus very close to the temperature of the surrounding ocean. Since IR measures surface temperature, during this time the temperature contrast between ice and water becomes small, rendering the extraction of sea ice concentration impossible for IR data; however, IR is usable during summer when the surface temperature is below freezing. Alternatively, although MODIS visible and near infrared data are not usable during polar darkness, they have very distinct spectral signatures against the ocean background and cloud cover and thus are well suited for daylight conditions. These signatures have not been

implemented in a standard MODIS product; it is desirable to explore the utilization of MODIS visible data for a summer sea ice concentration product as a necessary step toward a high-resolution year-round sea ice concentration data product.

The passive microwave and visible/IR fields can be combined to create an overall improved sea ice concentration field. This can then be tested in the ACNFS to determine the improvement in the model forecast fields. Currently, the ACNFS assimilates near real-time sea ice concentration derived from SSMIS and AMSR2 by updating the initial ice concentration analysis fields along the ice edge. In the past year, NASA Goddard and NRL have generated a merged 4 km AMSR-E/MODIS ice concentration dataset that was used as the initial condition for each ACNFS model run. Daily analysis of the ice edge location indicated the ACNFS initialized using the merged AMSR-E/MODIS dataset has substantially lower ice edge error (on average 50 km vs 30 km) than the ACNFS initialized using the coarser SSMIS data for a month-long study in 2008.

As mentioned above, during the summer months the sea ice/snow surface temperatures are often at their melting temperatures, causing the temperature contrast between ice and water to become small and rendering the extraction of sea ice concentration impossible for IR data (Hall et al., 2004). In this second year of this study we focused our research on two major tasks: (1) exploring the utilization of MODIS visible data for a summer sea ice concentration product, which is also a necessary step toward a high resolution year-round sea ice concentration data product, and (2) developing an AMSR W-band algorithm to yield ice concentration data at 6.25 km resolution. The status and improvements of satellite data and their assimilation results are discussed in the next section below.

This project is built upon collaborations of three groups: NASA Goddard Space Flight Center (NASA/GSFC) in Greenbelt, MD, NRL/Oceanography Division located at Stennis Space Center (SSC), MS, and NRL/Remote Sensing Division located in Washington, DC. GSFC and NRL/DC will develop a consistent multi-sensor merged sea ice concentration data set that utilizes the best satellite data available, including AMSR-E/AMSR2, MODIS and VIIRS, and will develop the operational processing of those data and make them available to NRL/SSC. New satellite algorithms will be developed to integrate passive microwave and Vis/NIR/IR sea ice concentration data consistently and optimally in terms of spatial coverage and resolution. NRL/SSC will incorporate the improved sea ice concentration dataset in ACNFS, perform an assessment of forecast improvements, and eventually assimilate this new dataset into the operational ice forecast system.

WORK COMPLETED AND RESULTS

The first two years of the study involved gathering the data products, evaluating the products, developing and testing the methods (particularly the MODIS ice concentration method), and integrating the MODIS and AMSR concentration estimates into a fused product. These tasks are described in the previous annual reports. In the final year, we completed these tasks, produced a one-year fused concentration product and evaluated its effect on the ACNFS forecast. These tasks meet the original statements of work outlined the original proposal. Here we summarize the tasks and the work done over the course of the project to complete the tasks. Tasks from Years 1 and 2 are only briefly summarized, as they were addressed in previous yearly reports.

a) Development of a consistent land mask

The AMSR, MODIS, and ACNFS model land masks were not consistent, presenting problems when integrated the observations together and assimilating into the model. The NRL ACNFS land mask was selected as the common land mask and was implemented in year one and is applied to all of the products. The NRL ACNFS land mask is very similar to the MODIS land mask and either results from either differed by only a small amount. The NRL ACNFS land mask provides the best consistency with the model. The land mask and all observed products use EASE grid with a resolution of 4 km.

b) Utilization of both visible and infrared data for year-round products

MODIS was selected as the source for the visible/IR products because of wide-availability, long heritage, well validated products, and familiarity with the sensor and sensor products within the research team. For summer, visible and near infrared channels are employed in a method by developed by Li and others at NRL/RSD. A sea ice classification algorithm was developed based on the spectral analysis of the MODIS high-resolution (500 m) data. The algorithm uses combinations of MODIS visible and near infrared (NIR) bands to separate different surface types. For our purpose of calculating sea ice concentration, we grouped surface types into five classes: sea ice, snow on sea ice, cloud, water, and land. The land surface type is determined by the 250 m resolution MODIS land mask data; the water surface is identified as very low albedo in the visible spectrum; ice/snow/cloud pixels are characterized and separated by their strong visible reflectance and strong short-wave IR absorbing characteristics, represented by the NDSI (Normalized Difference Snow Index); additional high and thin cloud screening is performed using the MODIS 1.38μm channel. Using this 500 m resolution sea ice classification data, sea ice concentrations were calculated at a degraded 4 km resolution and projected onto the 4 km EASE-grid. The ice concentration is performed on MODIS swath data then converted to 4km EASE-grid to be merged with AMSR-E data.

For winter, the ice surface temperature (IST) could be employed in the fused concentration product – ice is assumed to be present when (IST) is below the freezing point and water is assumed to be present when the IST is above the freezing point (Hall et al., 2004; Riggs et al., 2006). This approach is primarily valid for the winter growth seasons because as soon as surface melt begins on the ice, IST over ice and water becomes largely isothermal. In the initial delivered-version of the product, we focused on the visible/NIR component and it is used for the full year; IST is not used. The visible/NIR performance is limited during winter due to lack of sunlight. However, the method is still effective at high zenith angles and the ice edge is far enough south during much of the winter period that the visible/NIR imagery can be used. Because the visible MODIS channels dim above a certain solar zenith angle, the MODIS 02 product processing has a cutoff at 93.4 degrees solar zenith, above which it ceases to report visible channels. We found that this cutoff was too high for our algorithm to work. Based on a few specific case studies, we decided to not use visible MODIS channels when the solar zenith angle is above 89.0 degrees. Since the ice edge is the focus for forecasts, the winter visible/NIR imagery can still yield useful improvements to the model forecasts.

After the 4 km MODIS ice concentration data product is produced, it is merged with the AMSR2 10 km (resampled also to 4 km EASE-grid) ice concentration data, to create a merged 4 km AMSR2/MODIS dataset s. As a first step, we assume that the MODIS 500 m resolution cells that are classified as water or ice have 0% or 100% ice concentration, respectively. This is an approximation, but is reasonable at such small scales and current MODIS results are found to be sufficient for integration with lower resolution passive microwave data. The blended products use AMSR2 ice

concentration except in two conditions: (1) AMSR2 has great than 40% ice concentration and MODIS detected ice; (2) AMSR2 detected ice but has ice concentration less than 40%. In both cases, the MODIS ice concentration is used. The blending procedure is overly conservation to avoid small cloud effects in the optical data, and could reduce the benefit of MODIS data for low concentration, thin or heavily melting ice conditions. We are currently working on an algorithm to remove completely the cloud effects, which could result in significant improvement in the blended products.

An example result is provided in Figure 1. The greater detail provided by MODIS compared to AMSR2 in the clear sky regions is apparent. Also, the MODIS concentrations are generally higher than AMSR2, which correct the well-known low bias in passive microwave concentrations during summer melt. Finally, the MODIS ice edge extends farther than AMSR2, which is in agreement with visual inspection of the MODIS reflectance image (Figure 1a) and is not surprising because passive microwave algorithms may not detect thin, melting ice near the edge. There is discontinuity between the MODIS region (Figure 1b) and the AMSR2 region (Figure 1c) at the boundary of the MODIS swath edge (Figure 1d). This could potentially be resolved or at least reduced by adjusting AMSR2 concentration or algorithm coefficients so that the passive microwave estimates are consistent with MODIS. Nonetheless, the current product does provide improved fields in clear-sky regions.

c) Near-real time and operational processing; investigation of future data sources

At the beginning of this project AMSR2 data was not yet available; the only near real-time (NRT) passive microwave source was SSMIS that ACNFS was already using. We started looking at a test-case time period in 2008 when AMSR-E data was available. However, AMSR2 data is now available and there is an agreement between JAXA and NOAA for NOAA to receive AMSR2 data in near real time, NRL also has access to this data stream.

Therefore, in the past year we switched from 2008 AMSR-E data to 2014 AMSR2 data for the final development and testing. NRL is now receiving the AMSR2 NRT data stream and has incorporated it into the operational ACNFS runs. The MODIS data is also available in NRT and also being received at NRL. As resources are available at NRL, the combined MODIS-AMSR2 product will be implemented in NRT.

VIIRS data has also become available since the beginning of this product. This is a natural successor to MODIS, and ultimately preferable because it is expected to be the operational polar orbiting multi-spectral radiometer for many years to come. The two MODIS instruments, while still functioning well, are both well passed their planned lifetime and they cannot be relied on long-term. Some consideration was given to switching to VIIRS. However, a MODIS to VIIRS transition is more complicated than for passive microwave because the channels, algorithms, and products are different. Thus, such as switch was determined amongst the team to be high-risk, and to satisfy the goals of this project MODIS should continue be used. We have submitted an unsolicited white paper proposal to implement the high-resolution blended ice concentration product with VIIRS.

d) Implementation into ACNFS

Currently, the U.S. Navy's ACNFS is providing sea ice forecasts to the joint Navy/Coast Guard/National Oceanic and Atmospheric Administration (NOAA)/National Ice Center (NIC) as one source of information (along with satellite imagery) in determining ice edge location for the Arctic region. ACNFS is a 1/12° coupled sea ice and ocean model (Posey et al., 2010) that forecasts sea ice

conditions in the northern hemisphere poleward of 40° N. The horizontal resolution of ACNFS is 3.5 km near the North Pole and 6.5 km near 40°N (Figure 2). ACNFS is based on the HYbrid Coordinate Ocean Model (HYCOM) (Metzger et al., 2008; 2010) coupled to the Los Alamos National Laboratory Community Ice CodE (CICE) (Hunke and Lipscomb, 2008) and uses the Navy Coupled Ocean Data Assimilation (NCODA) system (Cummings, 2005). ACNFS has undergone validation by the Naval Research Laboratory (Posey et al., 2010) and has been transitioned to the Naval Oceanographic Office (NAVOCEANO) for operations. ACNFS is updated daily with observed sea ice concentrations.

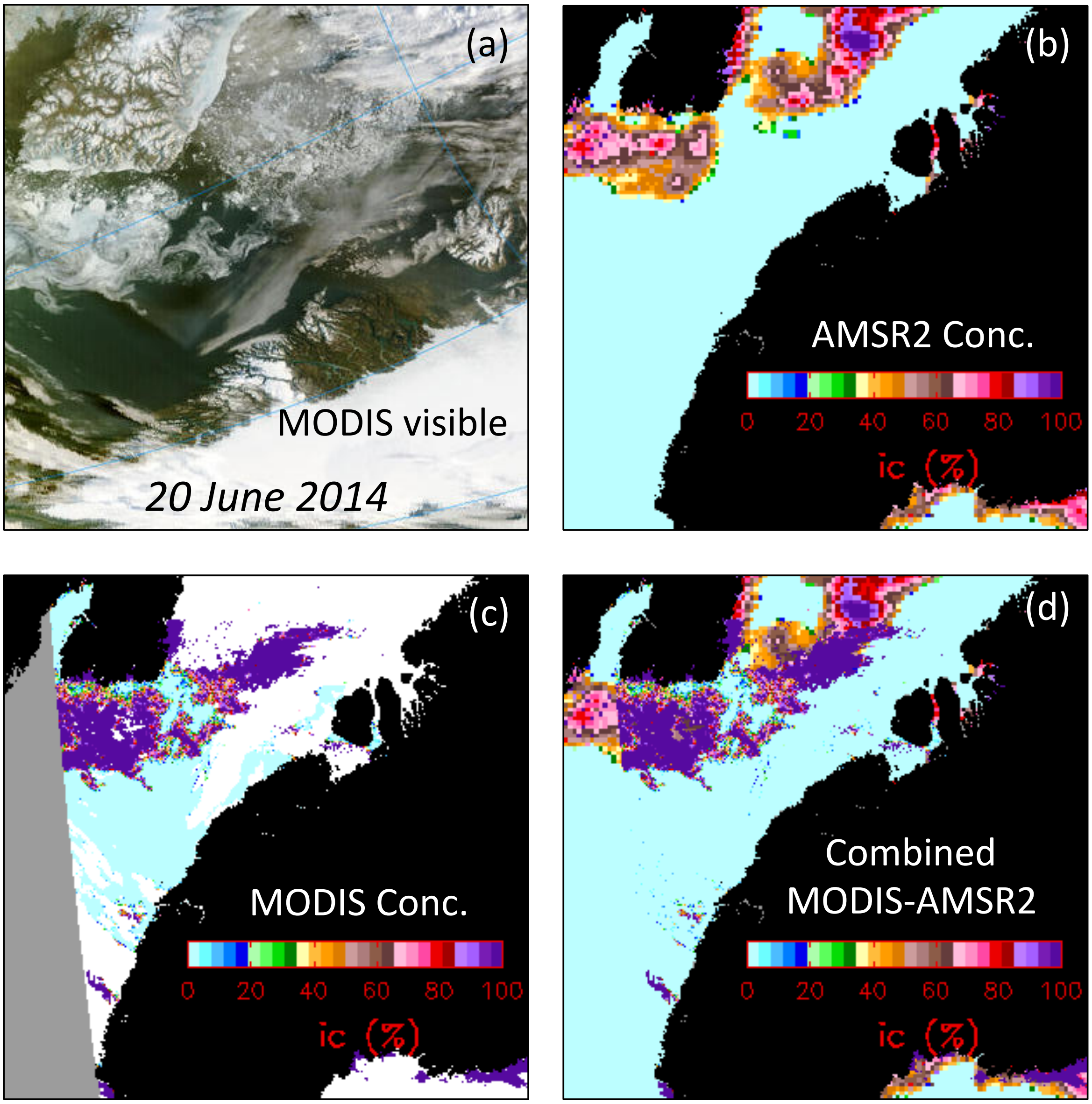

Figure 1. Example of combined concentration product in the Baffin Bay region on 20 June 2014, with (a) input MODIS visible reflectance image, (b) AMSR2 concentration, (c) MODIS concentration (clouds are in white), and (d) combined MODIS-AMSR2 field.

The current operational ACNFS assimilates near real-time sea ice concentration derived from SSMIS and AMSR2 each day and generates a daily initialization ice concentration field. SSMIS and AMSR2 derived ice concentrations are directly inserted into the ice model along the MIZ, defined here as areas

near the ice edge where ice concentration was less than 15%. The assimilation continues in ACNFS by using a weighting technique of the SSMIS/AMSR2 and model ice concentration in areas where concentration is between 15 and 40%; more weight is put on the model value (and less on SSMIS/AMSR2) as the model ice concentration approaches 40%. No ice concentration is assimilated where the ACNFS ice concentration is above 40%.

The SSMIS input was replaced by AMSR2 and then the combined MODIS-AMSR2 concentrations over a 1-year test period using 2014 data. Comparison was also made with a combined U.S. National Ice Center (NIC) daily Interactive Multisensor Snow and Ice Mapping System (IMS) sea ice extent field that was produced under a separate project (Meier et al., 2015; Posey et al., 2015). The operational ACNFS during this time period assimilated only the SSMIS ice concentration product. Three assimilation runs were performed using ACNFS for 1 January – 31 December 2014:

1. AMSR2 only
2. MODIS-AMSR2 combined
3. IMS-AMSR2 combined

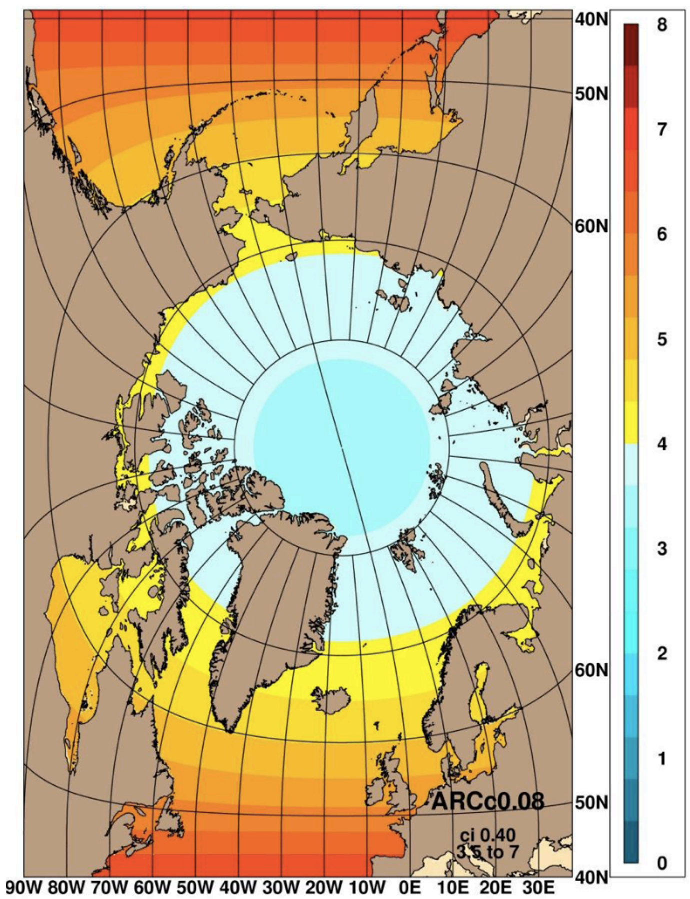

Figure 2. Map of ACNFS grid. Grid resolution is latitude dependent, as indicated by the color bar (scale in km). Most of the Arctic is 3-4 km resolution.

The forecasts of each were assessed by calculating daily errors between the model forecast ice edge and the observed ice edge location determined from the NIC daily ice edge location product. Note the NIC daily ice edge product is produced independently from the IMS product, though both are manual analysis and both often use common source data. Results were produced for Arctic wide and for separate regions in the Arctic (Figure 3).

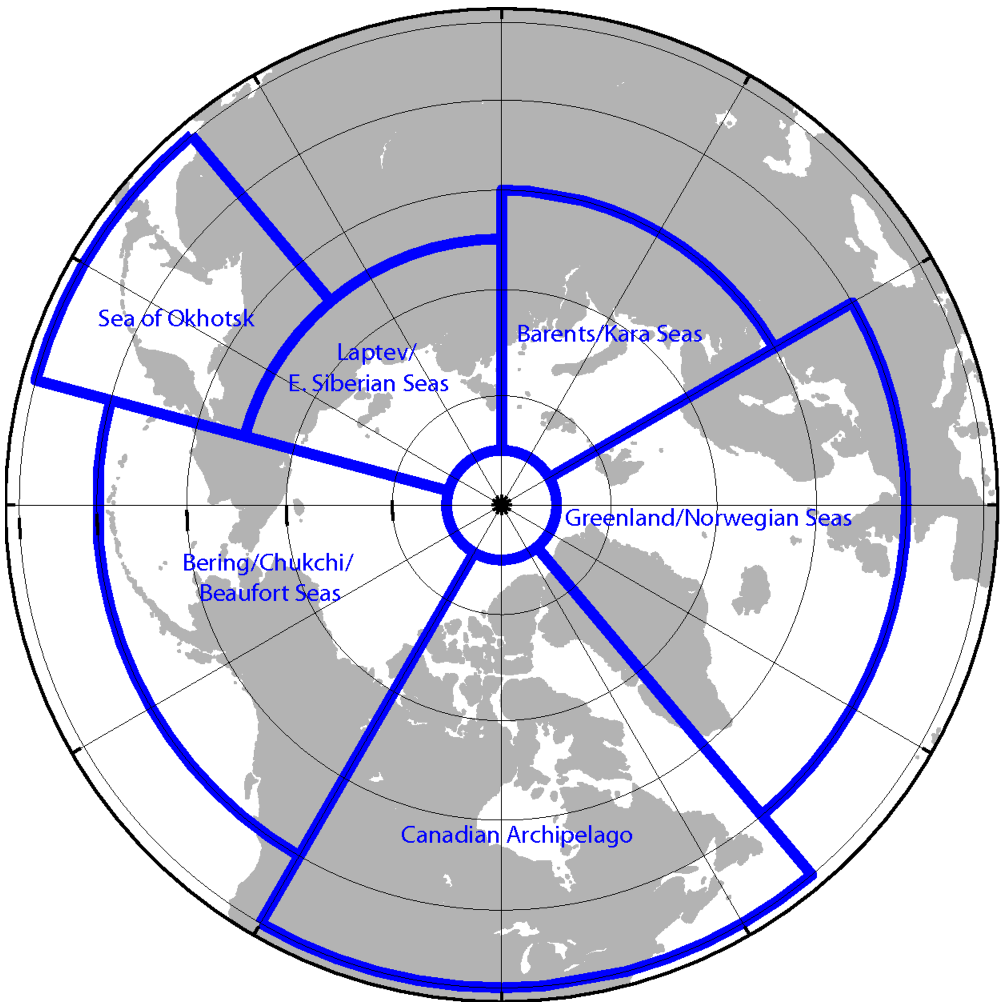

Figure 3. Defined regions for comparisons.

The results for whole Arctic (Figure 4) and the subregions (Figures 5-7) indicate substantial improvement and reduced ice edge errors over the current SSMIS initialization, even by replacing SSMIS with AMSR2 only. This is due to the much higher spatial resolution and sampling of AMSR2 that provides a more precise and accurate edge location than is feasible with SSMIS. Combining MODIS with AMSR2 yields further improvements. Not surprisingly, the combined IMS-AMSR2 showed the best results. As noted above, IMS is produced separately from the validation NIC ice edge dataset. However, in reality the two products are not completely independent since both use the same input imagery and both employ human manual analysis of that imagery (while the analysts may be different, training on image interpretation is consistent and analysts often move between duties). Nonetheless, there are days when IMS has much larger errors, such as in October and December (Figure 4). These may be due to errors in the IMS analysis due to human error, lack of imagery, limited image quality, or a combination of all three. This highlights that fact that although the IMS-based

product is overall better on most days, it is subject to inconsistencies from human factors, while the combined MODIS-AMSR2 is objective and thus its errors may be more systematic, predictable, and quantifiable.

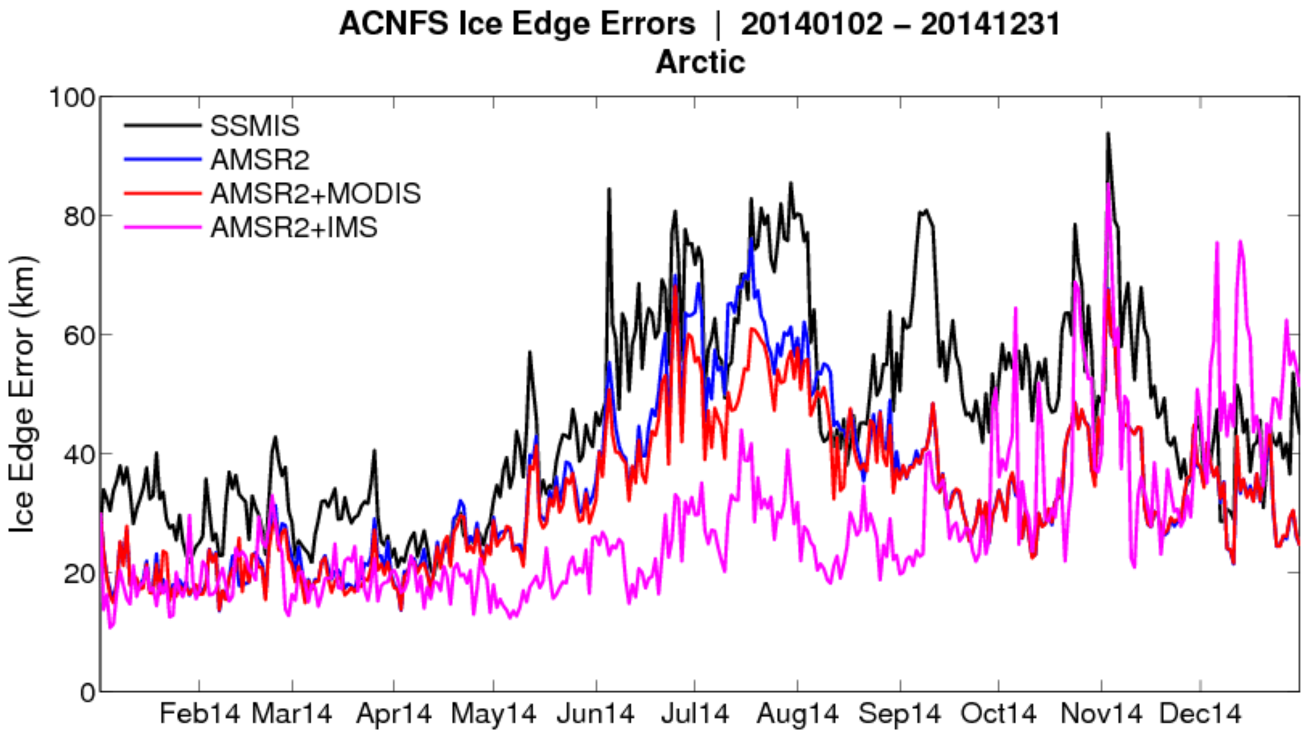

Figure 4. Daily ice edge error (km) over the entire Arctic for 2014 for SSMIS (black), AMSR2 (blue), MODIS-AMSR2 (red), and IMS-AMSR2 (magenta).

Examining the errors regionally provides more insight into the evaluation because conditions vary considerably in different regions of the Arctic at different times of year. The regional results are summarized in Table 1. The improvements seen in the total Arctic ice edge error is consistent throughout all regions, with the largest errors for SSMIS and subsequently smaller errors going to AMSR2, combined MODIS-AMSR2, and combined IMS-AMSR2. This suggests the results are quite robust, and indeed this is seen regional time series plots such as in the Barents/Kara seas (Figure 5). where the same daily pattern including higher IMS-AMSR2 errors in October and December are seen. The Bering/Chukchi/Beaufort seas regions also show a similar pattern, though not as pronounced (plot not shown).

As expected, the errors are generally higher during summer when the passive microwave errors are highest and the ice is less compact, yielding a more dynamic and more variable ice edge. Examining the summer daily errors more closely in the Barents/Kara seas region (Figure 6) and the Bering/Chukchi/Beaufort seas region (Figure 7) indicates that SSMIS errors can be quite large (>150 km) at times (e.g., mid-August for Barents/Kara, late July and mid-September for Bering/Beaufort/Chukchi). In contrast, using AMSR2 and the combined products substantially reduces the error during this time. The summer statistics for all regions are summarized in Table 2. The errors

are larger than the full-year statistics, as expected, but as seen with the full year study, using AMSR2 and the combined products yields lower errors than from SSMIS.

Table 1. Ice edge error (km) by region over 1 January – 31 December 2014 and percent improvement over SSMIS (last row)

Region	SSMIS only	AMSR2 only	AMSR2+ MODIS	AMSR2+ IMS
Greenland and Norwegian Seas	35	27	26	21
Barents and Kara Seas	30	25	24	23
Laptev and E. Siberian Seas	47	39	36	33
Sea of Okhotsk	46	32	30	28
Bering, Chukchi, and Beaufort Seas	49	35	33	28
Canadian Archipelago	58	44	41	39
Arctic	44	33	32	28
Improvement over SSMIS for total Arctic region	---	**25%**	**27%**	**36%**

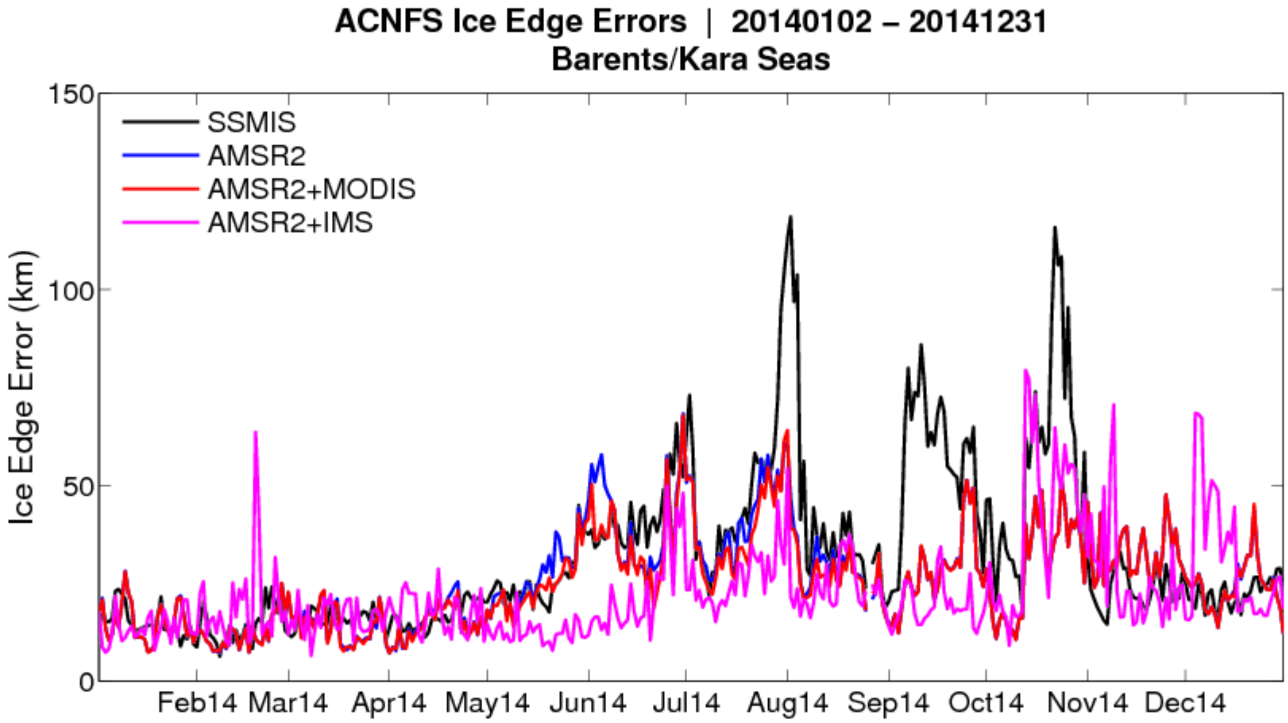

Figure 5. Daily ice edge error (km) for the Barents and Kara seas region for 2014 for SSMIS (black), AMSR2 (blue), MODIS-AMSR2 (red), and IMS-AMSR2 (magenta). Note that the y-axis range is larger than for Figure 4.

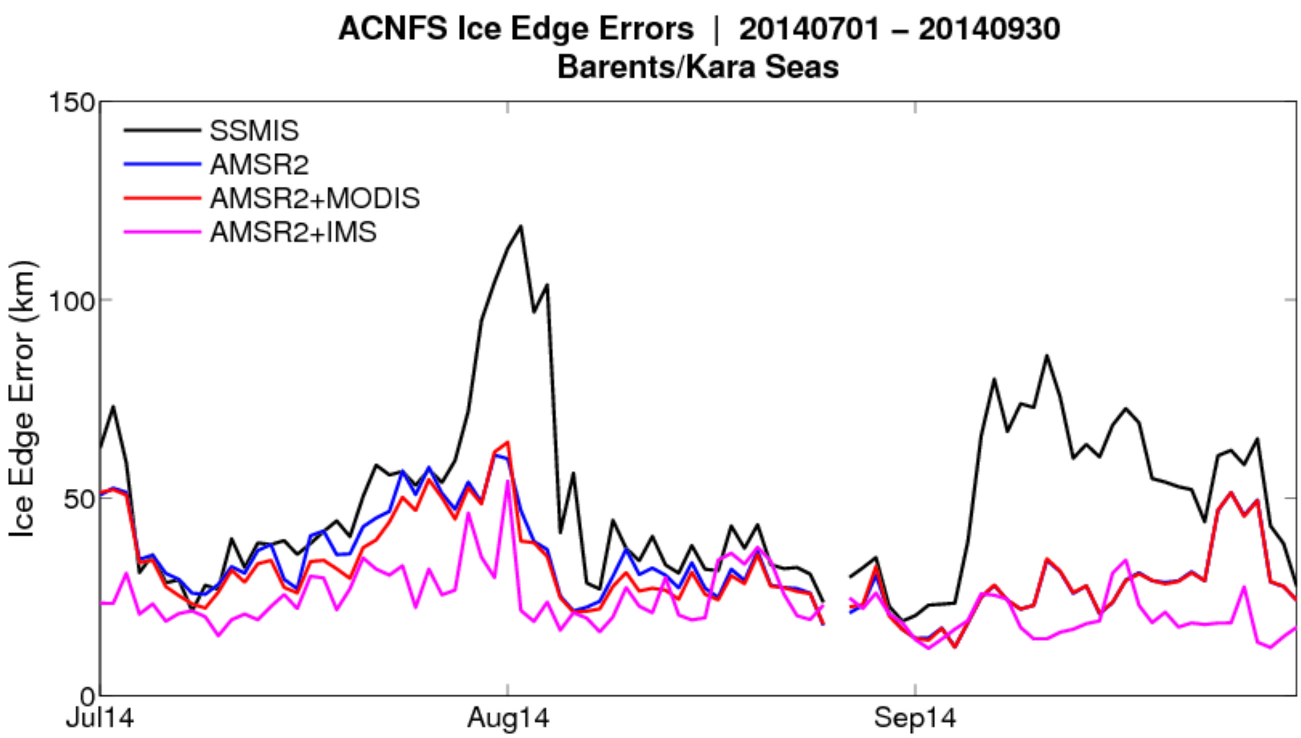

Figure 6. Daily ice edge error (km) for the Barents and Kara seas region for 14 July – 30 September 2014 for SSMIS (black), AMSR2 (blue), MODIS-AMSR2 (red), and IMS-AMSR2 (magenta).

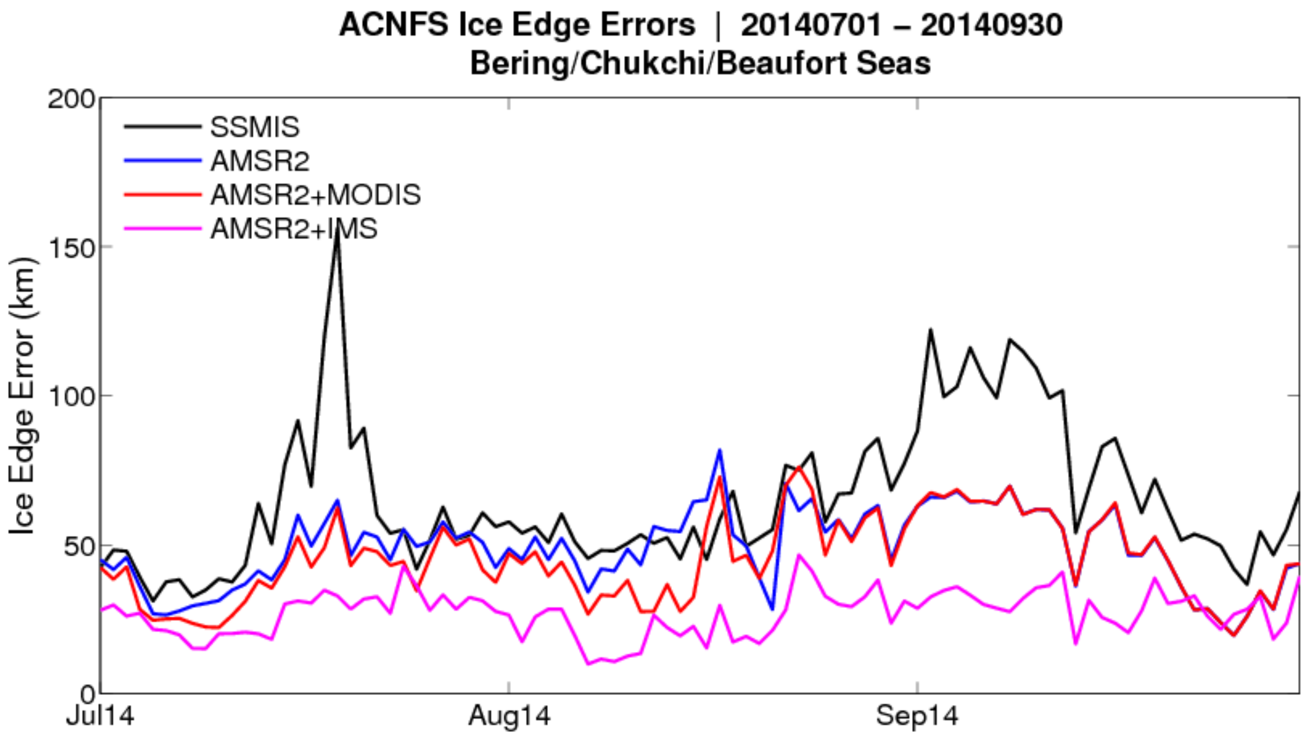

Figure 7. Daily ice edge error (km) for the Bering/Chukchi/Beaufort seas region for 14 July – 30 September 2014 for SSMIS (black), AMSR2 (blue), MODIS-AMSR2 (red), and IMS-AMSR2 (magenta). Note that the y-axis range is larger than in Figures 5 and 6.

Summary

In this study, a blended MODIS-AMSR dataset was developed and implemented. The dataset was then interpolated to the ACNFS model (3.5-6.5 km grid spacing) and assimilated to create the initial condition for each ACNFS model run. Once assimilated, model hindcasts of sea ice concentration were run and compared to the model hindcasts initialized from the coarse resolution SSMIS data only. This initialization study was initially performed for a one-month period, 1-30 June 2008, using AMSR-E. This analysis was updated and extended to a full year, 2014, using AMSR2 data. The daily mean distance error between the NIC ice edge location and the ice edge obtained from ACNFS initialized using SSMIS, ASMR2, the combined MODIS-AMSR2, and the combined IMS-AMSR2 data sets was calculated. Daily analyses of the ice edge location indicated that ACNFS initialized using the MODIS-AMSR2 data set has substantially lower ice edge error (on average from 44 km to 32 km) than the ACNFS initialized using the coarser SSMIS data. Studies also indicate that the ACNFS initialized using the blended dataset improves the ACNFS predicted ice edge location by a range of 25-30%, with an average Arctic-wide improvement of 27%.

Regionally, the improvements were shown to be even better than the full year study. In particular, during summer when errors are highest, the combined products (MODIS-AMSR2 and IMS-AMSR2) were especially effective, with errors dropping by as much as 53%. These results indicate that a combined visible/IR and passive microwave sea ice concentration product can substantially improve the quality of sea ice forecasts for the U.S. Navy.

Table 2. Ice edge error (km) by region over 1 July – 30 September 2014 and percent improvement over SSMIS (last row)

Region	**SSMIS only**	**AMSR2 only**	**AMSR2+ MODIS**	**AMSR2+ IMS**
Greenland and Norwegian Seas	64	49	44	21
Barents and Kara Seas	47	33	31	23
Laptev and E. Siberian Seas	48	44	40	30
Sea of Okhotsk	-	-	-	-
Bering, Chukchi, and Beaufort Seas	64	48	43	27
Canadian Archipelago	71	63	54	36
Arctic	60	48	43	28
Improvement over SSMIS for total Arctic region	---	**20%**	**28%**	**53%**

Future Work

While this project has reached its completion, there is the potential for future work to extend and further evaluate the results. A white paper proposal has been submitted to implement the combined method with VIIRS. While we do not expect a significant difference in performance, the use of the operational VIIRS sensor over the older, research-level MODIS products is an advantage for an operational model such as ACNFS and is essential for long-term viability of the product since the MODIS instruments are well beyond their planned lifetime. We also propose to perform further intercomparison between products including the MODIS-AMSR2 and VIIRS-AMSR2, as well as the IMS-AMSR2, to better assess the differences between each product and help guide the Navy in deciding which product to ultimately use operationally or whether there is value to using multiple products.

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